

Formation Scenarios

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Abstract: I discuss various proposed formation scenarios for the metal-poor components of the Milky Way Galaxy, emphasising the stellar halo and the thick disk. Interactions and accretion played a significant role in Galactic evolution, in particular at earlier epochs. The present observations favour a scenario by which the thick disk formed through the heating of a pre-existing thin stellar disk, with the heating mechanism being the merging of a satellite galaxy. A remnant ‘moving group’ of the satellite would provide strong support for this scenario, and may have been detected. The field stars in the stellar halo probably formed in early small-scale star-forming regions, which subsequently disrupted. Late accretion is not important for the bulk of the stellar halo. The stellar initial mass function shows no evidence of variations, and indeed shows evidence of being invariant, even in companion satellite galaxies.

1 Introduction

In keeping with the focus of the Colloquium, I will discuss primarily the formation of the thick disk and of the stellar halo, the more metal-poor components of the Milky Way Galaxy. However, we should bear in mind that at approximately the same epoch at which these stars formed, around 12 or 14 Gyr ago, the stars in the central bulge were also forming (Ortolani *et al.* 1993; Feltzing & Gilmore 1999), despite the bulge stars being significantly more metal-rich in the mean than are stars in either the thick disk or the stellar halo. Further, there also exist old stars in the local thin disk, at least as old as 10 Gyr and perhaps as old as stars in the halo (e.g. Edvardsson *et al.* 1993), which could imply that there was no significant hiatus between halo and the onset of disk formation (we have little information for the age distribution of stars in the more distant thin disk, either interior or exterior to the solar circle). The existence of these old disk stars poses significant problems for some models of disk galaxy formation, such as those (Weil, Eke & Efstathiou 1998) that posit the delay of disk formation until after a redshift of unity, or lookback times of only ~ 7 Gyr for a flat matter-dominated Universe with Hubble constant of 65 km/s/Mpc.

Current structure formation scenarios favour hierarchical clustering, such as that in a universe dominated by cold, dark matter (CDM). In this picture, the first objects to turn around and collapse have a mass that is a small fraction of the mass of a galaxy like the Milky Way (e.g. Tegmark *et al.* 1997), and larger-scale structure grows by clustering and merging of this small-scale structure. The dynamics of the dark matter, interacting only through gravity,

is rather straightforward to model, through N-body simulations and semi-analytic techniques such as the Press-Schechter formalism (e.g. Lacey & Cole 1993). Following the behaviour of the baryons and predicting the evolution of luminous galaxies is much more difficult, either with gas-dynamic simulations (e.g. Navarro & Steinmetz 1997; Pearce *et al.* 1999) or star-formation prescriptions combined with the N-body simulations and/or semi-analytic treatment of the merging of the dark haloes (e.g. Kauffmann *et al.* 1999; Baugh *et al.* 1998). Cold dark matter models have found much success in the analysis of observations of large-scale structure, from the microwave background down to clusters of galaxies. Further, there are many examples in both the local, and distant, Universe of interacting and merging galaxies. The Milky Way is clearly interacting with its satellite galaxies, such as the LMC/SMC (Putman *et al.* 1998) and the Sagittarius dwarf spheroidal galaxy (Ibata, Gilmore & Irwin 1994; 1995).

However, disk galaxies as observed, with a broad range of stellar ages in the thin disk, cannot have experienced merger events that were too frequent or too violent, since this would have destroyed the disk (cf. Ostriker 1990; Toth & Ostriker 1992). The past merging with dissipationless stellar or dark-matter systems is restricted to the accretion of small objects onto a dominant central system. And the accreted objects have to be assimilated quite efficiently, since at least in the Milky Way there is little evidence of successive, significant, past mergers.

This last point is particularly difficult in light of new high-resolution N-body simulations by two groups (Klypin *et al.* 1999; Moore *et al.* 1999a) which for the first time have enough dynamic range to model both large and small scales within the same simulation. These simulations have been restricted so far to flat ($\Omega = 1$) cosmologies, with CDM the dominant mass, and include a universe dominated by Λ at the present day ($\Omega_\Lambda = 0.7$, $\Omega_{CDM} = 1 - \Omega_\Lambda$), as favored by a variety of constraints on large scales (Bahcall *et al.* 1999). In these model universes, small-scale dark haloes are very persistent (essentially reflecting their high redshifts of formation and hence high density) and they predict that a galaxy like the Milky Way should today have around a factor of ten more satellite galaxies than we observe. Of course, the simulations are strictly restricted to dark haloes only, and one might postulate that the ‘missing’ satellites (cf. Klypin *et al.* 1999) are dark, or perhaps related to the extremely high-velocity clouds identified by Blitz *et al.* (1999). However, even if dark, those satellites on radial orbits that interact with the disk of the Milky Way could make a *thin* disk impossible to sustain (Moore *et al.* 1999a).

Allowing an open universe, still dominated by CDM, would change the timescales of the growth of structure, but not remove the basic problem with the over-prediction of the number of long-lived satellite galaxies. The simulations of a flat universe provide very good agreement with observations on larger scales, such as the galaxy luminosity function within clusters of galaxies (Moore *et al.* 1999a), leading to the suggestion that some modification be made to the CDM power spectrum, to reduce small-scale power. Such a modification, truncating the power spectrum at small scales, may also be favoured by the discrepancies between the shapes of the galaxy rotation curves predicted by standard CDM-dominated models (Navarro, Frenk & White 1997) and the observations for dwarf galaxies (Moore 1994) and for other apparently dark-matter-dominated galaxies, such as low-surface-brightness disks (Burkert & Silk 1997; 1999; Moore *et al.* 1999b).

Indeed, many of the properties of present-day disks, for example their scale-lengths and rotational velocities, can be explained by simple dissipational collapse of gas within a fixed dark halo potential, with detailed conservation of angular momentum (Fall & Efstathiou 1980; Dalcanton *et al.* 1997; Mo, Mao & White 1998), followed by modest re-arrangement by, for example, viscous processes (e.g. Zhang & Wyse 2000). Merging of dark haloes and luminous galaxies is usually accompanied by angular-momentum transport, driven by gravitational torques and dynamical friction, removing angular momentum from the disk material, and ‘standard’ CDM-

dominated models produce disks that are too small (Navarro & Steinmetz 1997). Again, this suggests only ‘minor-mergers’ in the history of a disk galaxy. Of course the formation of stars is set by local gravitational instability, on the scale of giant molecular clouds and their cores.

Thus essentially all models of galaxy formation and evolution invoke early star formation in substructure, whether the smaller scales formed by fragmentation (perhaps reflecting the Jeans mass) or were primordial density fluctuations (such as the CDM power spectrum). Questions that both observation and theory should address include what fraction of this substructure survives to the present, what are the possible relationships of this early substructure with present-day smaller systems, e.g. dwarf galaxies or globular clusters, and how important are interactions with satellite galaxies? The faint stellar Initial Mass Function (IMF) in satellite galaxies of the Milky Way, which are possible examples of surviving ‘building blocks’, is also now accessible to direct determination. Local observations of old stars provide complementary constraints to observations of high redshift objects.

2 The Thick Disk

This stellar component was first detected in the Milky Way Galaxy through star counts (Gilmore & Reid 1983), although surface photometry of external S0 galaxies had earlier revealed ‘thick disks’ in them (Burstein 1979; Tsikoudi 1979). Perhaps the most recent study of the structure of the thick disk through star counts is that of Phleps *et al.* (1999), who utilised the R-band data in the NGP of the Calar Alto (faint galaxy) survey; they detect the thick disk, and derive parameter values that are reasonably consistent with earlier results, in that the scale-height of the thick disk is around 1kpc, and the local (solar neighbourhood) normalisation by number is several percent.

2.1 Connection to Other Galactic Components

At the time of its discovery, it was postulated that the thick disk was formed by local compression of the stellar halo by the potential of the thin disk (Gilmore & Reid 1983). This was soon disproven (Gilmore & Wyse 1985) by the determination of distinct metallicity distributions of thick disk and stellar halo (see Fig. 1 here).

But is the thick disk simply the extreme thin disk, meaning they have a common origin? An increase in scale-height and velocity dispersion with stellar age within the thin disk is well-established (e.g. Wielen 1977). However, the thick disk is discontinuous in its kinematics from the thin disk (Wyse & Gilmore 1986; Gilmore, Wyse & Kuijken 1989). Further, the value of the vertical velocity dispersion of the thick disk, some 40 – 45km/s (e.g. the review of Majewski 1993 and references therein) is too high to be explained by the known heating mechanisms for the stars in the thin disk, namely interactions with local gravitational perturbations in the disk, such as Giant Molecular Clouds (Spitzer & Schwartzschild 1957; Lacey 1991). More exotic phenomena, such as close encounters with massive black holes in the dark halo, can provide the required high amplitude of random motions for a small fraction of the thin-disk stars (Ostriker & Lacey 1985; see also Sanchez-Salcedo 1999), but then the thick disk should be a random sample of the thin disk, and have very a similar stellar population. Again, the different metallicity distributions of thick disk and thin disk argue against this – the metallicity distribution of the thick disk peaks at $[\text{Fe}/\text{H}] \sim -0.6$ dex, and is rather broad (Gilmore & Wyse 1985; Carney, Latham & Laird 1989; Wyse & Gilmore 1995; Bonifacio *et al.* 1999), while that of the thin disk peaks around -0.2 dex (e.g. Wyse & Gilmore 1995; see Fig. 1 above). Further, the thick disk is apparently composed of only old stars, ages older than ~ 12 Gyr (Gilmore

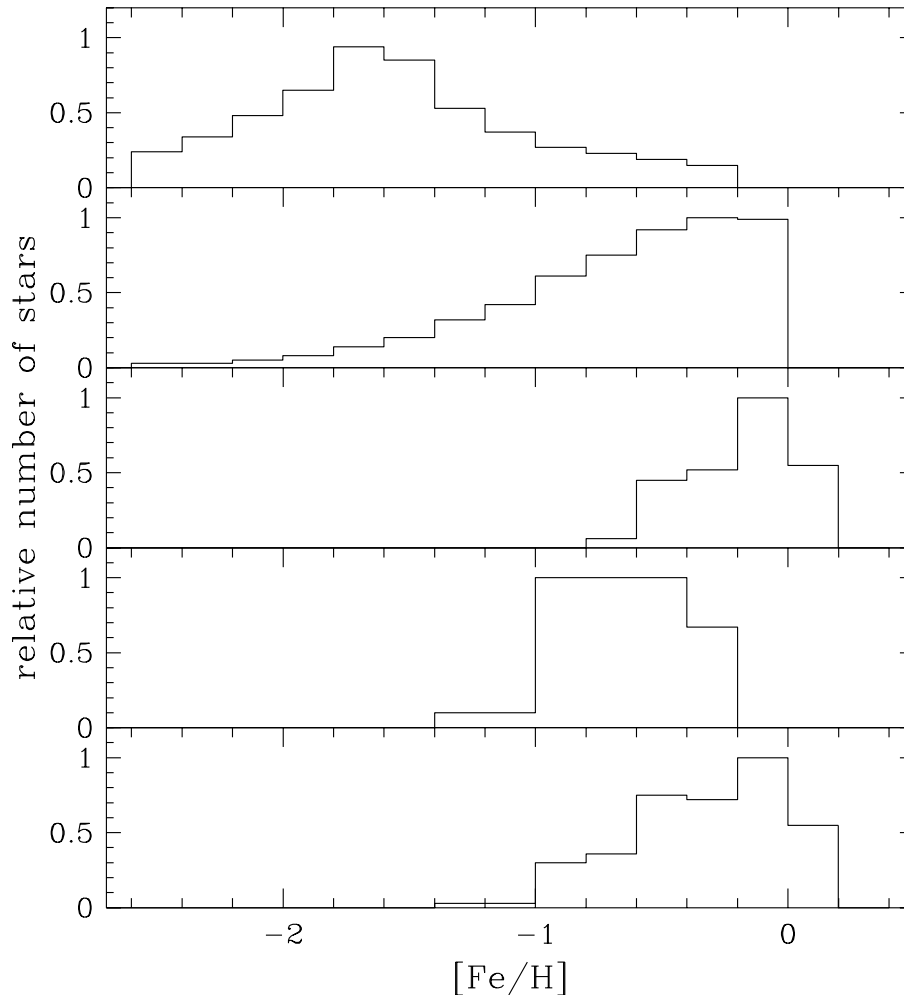


Figure 1: The metallicity distributions of representatives of the stellar populations of the Milky Way Galaxy. Where possible, a measure of the true iron abundance is plotted. The panels are (top to bottom) the local stellar halo (Carney *et al.* 1994, their kinematically-selected sample); the outer bulge K-giants (Ibata & Gilmore 1995), truncated at solar metallicity due to calibration limitations; the volume-complete local thin disk F/G stars (derived from the combination of the Gliese catalogue and *in situ* survey); the volume-complete local thick disk F/G stars (derived similarly); and lastly the ‘solar cylinder’, i.e. F/G stars integrated vertically from the disk plane to infinity. This figure is based on Fig. 16 of Wyse & Gilmore (1995).

& Wyse 1985; Gilmore, Wyse & Kuijken 1989; Carney, Latham & Laird 1989; Edvardsson *et al.* 1993; Gilmore, Wyse & Jones 1995; Fuhrmann 1998; Carney, this volume; Bartasiute & Lazauskaite, this volume). The age distribution older than this is not well-defined with present data, but a younger component must be only minor. This last point is illustrated in Fig. 2, and argues strongly against an extended period of thick disk formation, and in favour of a unique event, long ago.

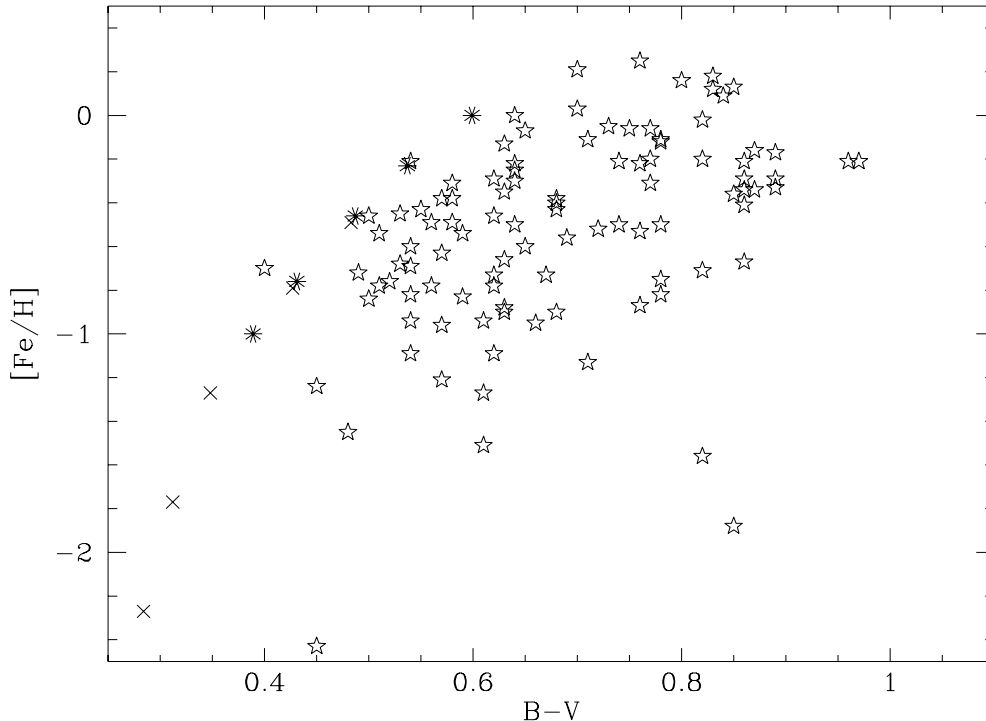


Figure 2: Scatter plot of iron abundance *vs* $B-V$ colour for thick disk F/G stars, selected *in situ* at 1-2kpc above the Galactic Plane (stars), together with the 12 Gyr turnoff colours (crosses) from Vandenberg & Bell (1985) and from Vandenberg (1985; asterisks). The vast majority of thick disk stars lie to the red of the 12 Gyr turnoff points, indicating that few, if any, stars in this population are younger than this age. This figure is based on Fig. 6 of Gilmore, Wyse & Jones (1995).

2.2 Heating or Cooling?

Two possibilities remain, one that the thick disk formed as part of the (dissipational) settling of the proto-thin disk, the second that the thick disk formed during a traumatic heating event early in the evolution of the thin disk. In the former (cooling) scenario the scaleheight of the stellar disk decreases with time, and is set by a balance between cooling (and star formation) and gravity; the discontinuity between thick and thin disks could reflect the change in the cooling law as metallicity increases above ~ -1 dex and line radiation from metals becomes dominant (Gilmore & Wyse 1985; Burkert, Truran & Hensler 1993; Burkert & Yoshii 1996). One might then expect all (moderately metal-rich) disk galaxies to have a thick disk, which they do not (e.g. Shaw & Gilmore 1990; Fry *et al.* 1999).

The latter (heating) scenario draws some support from the fact that, as noted above, interactions between the Milky Way and its satellites are ongoing. The vertical velocity dispersion of the thick disk can be provided for if a significant part of the orbital energy of a moderate-mass satellite galaxy is transformed into additional internal energy of the stellar thin disk (Gilmore & Wyse 1985; Ostriker 1990; Majewski 1993). The effect of the accretion of a companion galaxy on the disk depends on many parameters such as those of the satellite's orbit (initial inclination to the disk plane, pericenter and apocenter distances, sense of angular momentum) and the satellite's density profile and total mass. Simulations of the merging process between a stellar disk and satellite have become increasingly sophisticated in recent years, including

more physics such as allowing the excitation of the internal degrees of freedom of the dark halo, which lessens the heating effect on the disk (e.g. Huang & Carlberg 1997; Walker, Mihos & Hernquist 1996; Velazquez & White 1999). The extant simulations suggest that the accretion by the present-day stellar disk of a stellar satellite with mass some 20% of that of the disk can produce a thick disk similar to that observed in the Milky Way. However, gas has yet to be included in the simulations investigating disk heating, which is an important shortcoming, since gas if present (which is likely), would absorb and subsequently radiate away some of the orbital energy, again lessening the impact of the merger.

Further, the initial conditions of the published simulations assume a fully-assembled stellar disk, and especially given the results above on the old age of the Galactic thick disk, we need simulations that better model conditions at an early stage of disk galaxy evolution. The stellar population in the local thin disk is consistent with a roughly constant star-formation rate over a Hubble time (e.g. Rocha-Pinto & Maciel 1997), implying that the local stellar disk at the lookback time corresponding to the formation of the thick disk was around 10% of its present mass. This is close to the mass of the local thick disk, expressed as a fraction by mass of the present-day local thin disk, suggesting essentially all of the pre-existing thin disk was heated. Of course one needs to know how to generalise this result to the entire disk, which requires global knowledge of star-formation histories and thin- and thick-disk structural parameters. Further, the energy losses due to gas have yet to be taken into account. Really one needs a cosmologically self-consistent model including disk buildup, with appropriate star formation.

As a corollary to this heating scenario, if a significantly massive satellite were responsible for the thick disk, the accompanying torques could drive a substantial fraction of the gas in the disk at that time to the central regions, perhaps triggering rapid star formation (cf. Hernquist & Mihos 1995) and even the formation of the ‘bulge’ (Minniti 1996) or ‘thick disk’ (Armandroff 1989) globular clusters. It may well be no coincidence that the ages of field stars in the bulge (e.g. Feltzing & Gilmore 1999) and in the thick disk are similar.

The lack of young or even intermediate-age stars in the thick disk limits the last significant merger to have occurred a long time ago, at lookback times greater than around 12 Gyr, or redshifts of ~ 6 in standard matter-dominated flat cosmology. This is rather difficult for $\Omega_{CDM} = 1$ models, requiring the Milky Way to be an unusual galaxy (cf. Toth & Ostriker 1992). Note that Moore *et al.* (1999a) argue that any hierarchical clustering cosmology, even the open CDM-dominated model, has problems since not all disk galaxies have thick disks. However, I feel that given the many parameters determining the effect of a merger on a disk, a widely disparate population of thick disks, including one too small to have been detected, must result.

2.3 Where is the Shredded Satellite?

Is there then a signature of the remnant of the putative satellite that caused the Milky Way thick disk? Stars that are removed by tides will remain on orbits close to that of the centre-of-mass of the satellite at the time the stars are removed (e.g. Tremaine 1993; Johnston 1998); the orbit of the satellite is expected to decay through dynamical friction (at a rate dependent on its mass, but the effect should be significant for the $\sim 20\%$ fractional masses under consideration), depositing ‘shredded satellite’ stars over a reasonably large spatial region. These stars will phase mix. Published simulations of low-inclination satellite orbits indeed show that the satellite is dispersed into a broadly flattened distribution, mixed in with the heated thin-disk stars. Satellites on prograde (rather than retrograde) orbits couple better to the disk and provide more heating, and are favoured to cause the thick disk (e.g. Velazquez & White 1999). Thus one might expect a signature to be visible in the mean orbital rotational velocity of the stars,

and for a typical satellite orbit in the mean the stripped stars would lag the Sun by more than does the canonical thick disk. The relative number of stars in the ‘shredded satellite’ versus the heated-thin disk (now the thick disk) depends on the details of the shredding and heating processes, and is a diagnostic of them, and may well vary strongly with location. Note that a merger without accompanying heating of the disk, but producing the thick disk in its entirety from the shredded satellite is rather contrived: this would require a fairly massive satellite, given what we know of the mass-metallicity relationship and the relatively high mean metallicity of the thick disk – which at ~ -0.6 dex is greater than that of the old population in the LMC, and about equal to the young population in the SMC (see, e.g. de Freitas Pacheco, Barbuy & Idiart 1998) – and also the total luminosity of the thick disk, extrapolated from its locally-defined structural parameters (several percent of the present thin disk). Only a very narrow part of parameter space could allow a satellite this massive to penetrate even to the solar circle, then be tidally disrupted without imparting any damage to the thin disk.

We (Gilmore, Wyse, Norris & Freeman) are quantifying the phase-space structure of the Milky Way, through a comprehensive statistical study of the kinematics and metallicity distributions of stars in the interface between the thick disk and stellar halo, those stellar components for which mergers are most often implicated. We are using the 2-degree-field fibre-fed spectrograph on the Anglo-Australian telescope, providing 400 spectra simultaneously. These spectra are used to obtain radial velocities and absorption line-strengths for samples of F/G main sequence stars at distances from the Sun of 5–10kpc (dependent on metallicity and magnitude), beyond significant contamination by the thin disk, down several key lines-of-sight. Our targets include fields towards and against Galactic rotation, to provide optimal halo/thick disk discrimination through orbital angular momentum. Further, we have fields at the same Galactic longitude but different latitudes, to determine if any kinematic features are halo-like or disk-like in their spatial distributions. We also include lines-of-sight interior to and exterior to the Sun, to allow characterisation of the velocity dispersion tensor, detection of gradients and any metallicity–kinematics correlation, and crucially to test if kinematic structure is restricted to angular momentum, or is equally present in the other components of the velocity tensor. Our approach investigates the time-integrated structure of the halo and thick disk and is quite complementary to surveys of the far outer Galaxy.

Our first observations have apparently detected a new kinematic component of the Milky Way Galaxy, plausibly the shredded remnant of the satellite whose merger with the Galaxy produced the canonical thick disk, by heating the pre-existing thin disk. As described above, depending on the mass, density profile and orbit of the satellite, ‘shredded-satellite’ stars will leave a kinematic signature, distinct from the canonical thick disk that results from the heated thin disk. As shown in Fig. 3 and Fig. 4 below, the radial velocity distributions for our samples indeed show evidence for an excess number of stars moving on orbits with V-velocity between those of the canonical thick disk and halo, with a low velocity dispersion, plausibly smaller than either of these Galactic components, and further this signature is strongest in the blue stars.

A similar kinematic signature was seen in our earlier *in situ* (AUTOFIB) survey of the kinematics and metallicity distributions of stars in the thin disk/thick disk interface (Wyse & Gilmore 1990). Further, Fuchs *et al.* (1999) have reported a similar result, finding an excess number of stars with intermediate kinematics in a narrow metallicity range, for a local sample, based on the kinematically-selected sample of Carney *et al.* (1996), supplemented with Hipparcos data. These stars are best interpreted as being the actual debris of the satellite and would provide the ‘smoking gun’ signature of the most significant merger in the Galaxy’s past. They must be part of a fairly large system, being detected in disparate samples, but this requires a

larger statistically-significant sample for confirmation, to allow quantification of the properties of the satellite galaxy, and to distinguish between this interpretation and a vertical gradient in the mean rotation of the thick disk (e.g. Majewski 1993; Mendez *et al.* 1999). The metallicity distribution will be an important constraint, reflecting that of the parent satellite in one case (cf. Freeman 1993), and that intrinsic to the thick disk in the other (that of the old thin disk, should the canonical thick disk be the heated thin disk).

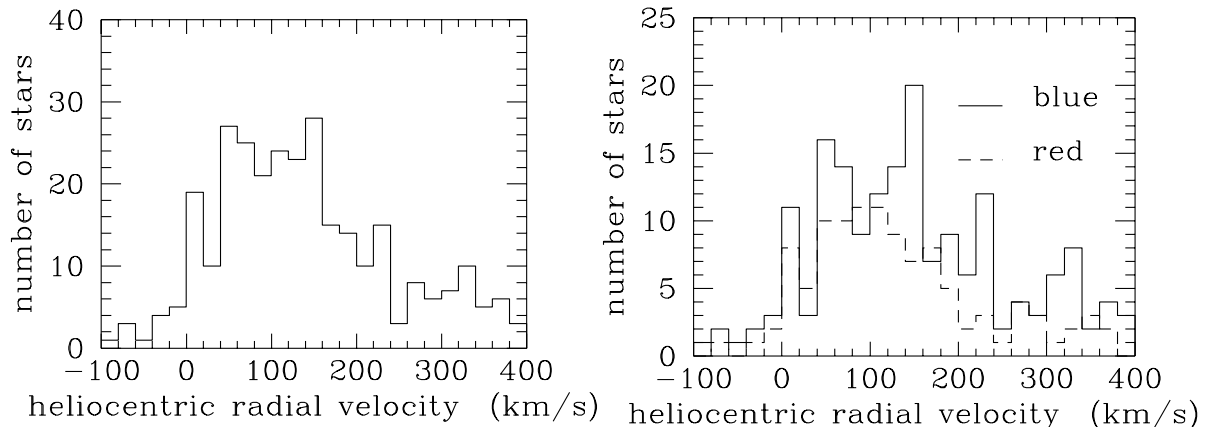


Figure 3: Histograms of the heliocentric radial velocity for the field at ($\ell = 270$, $b = +33$); this line-of-sight was chosen to probe the orbital angular momentum of the stars, with $v_{\text{radial}} = -0.84V + 0.54W$. The left panel shows all the stars from one observing run, while the right panel shows them divided by colour. The standard, slightly-prograde, stellar halo would have a fairly broad radial velocity distribution peaking at around 200km/s and dispersion of 100km/s (see Fig. 4 below), and the thick disk peaking at around 25km/s, with dispersion of 55km/s. There is an apparent excess of stars with line-of-sight velocity intermediate to these peaks, and a poorly-defined but low dispersion, and the signature is stronger for the bluer stars.

3 The Stellar Halo

To first order, the stellar halo is the metal-poor, old, slowly-rotating, extended but centrally-concentrated, stellar system represented at the solar neighbourhood by the high-velocity subdwarfs. The stellar halo is usually distinguished from the central bulge when discussing the Milky Way, but it is common practice simply to refer to them as one entity – the bulge or spheroid – in discussions of external disk galaxies (see Wyse, Gilmore & Franx 1997 for a review). This is of course related to the difficulty of detecting a component like the stellar halo in external galaxies – the mass ratio between bulge and stellar halo in the Milky Way is around a factor of ten, and the surface brightness of the stellar halo at the solar circle is around 28 mag/sq arcsec in the B-band (Morrison 1993).

Essentially all models of the formation and evolution of the stellar halo invoke early star formation in small substructure, with subsequent disruption of these systems and mixing and assimilation of the stars formed therein into the field stellar halo. The small substructure may have formed through fragmentation of an initially ‘monolithic’ baryonic component, perhaps reflecting the Jeans mass of shock-heated gas in the potential well of a larger-scale protogalaxy (e.g. Fall & Rees 1985), or could reflect simply the initial power spectrum of primordial density

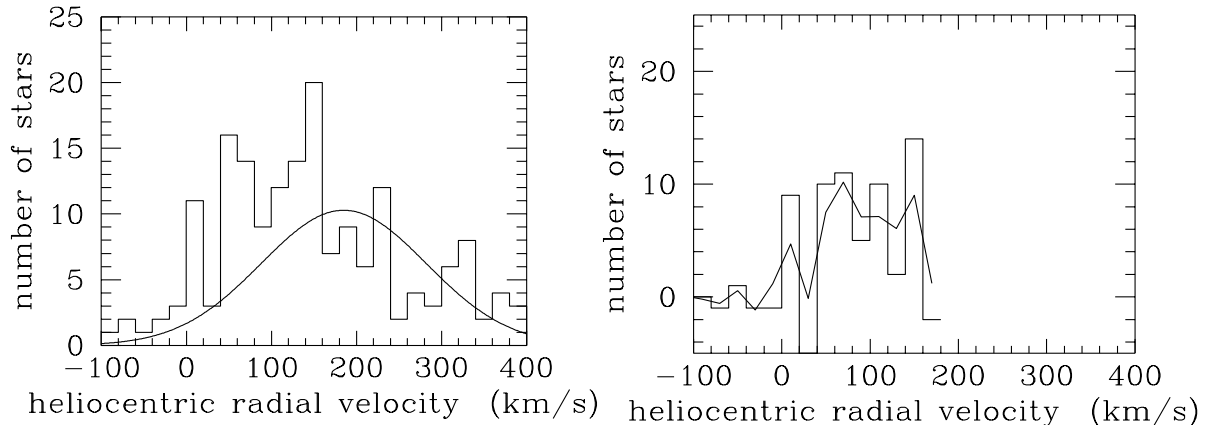


Figure 4: The left panel is all the blue stars from Fig. 3, with the predictions in this line-of-sight for a standard, slightly-prograde, halo. The right panel is the ‘excess population’ (plus a running mean) obtained by reflecting the data about the mean of this symmetric distribution function.

fluctuations (e.g. White & Rees 1978). Or, a combination of the above. It is highly likely that the stellar halo is ‘multi-component’ and we need to quantify the stellar masses in the different components, and characterise their origins.

Questions that can be addressed and hopefully answered by the fossil record of the halo stars include – when did the stars form? Did internal (e.g. feedback from massive stars) or external (e.g. collisions or tidal disruption) processes cause the destruction of the substructure? When was the substructure disrupted? What is the relation, if any, between this putative substructure and surviving systems in the halo such as globular clusters and satellite galaxies? What is the relationship to ‘Population III’, those stars formed very early, at redshifts prior to re-heating and re-ionization of the InterGalactic Medium? Has accretion of stars and stellar systems played an important role?

3.1 Elemental Abundances

The chemical elemental abundances of a typical halo star are as expected if only Type II supernovae enriched the gas out of which the stars formed (e.g. Nissen *et al.* 1994; Norris 1999). The most straightforward explanation of this observation is that these stars formed in star-formation events that were of short duration, shorter than the time needed to have significant production of newly-synthesised material by Type Ia supernovae. While there is not yet a generally-accepted model of Type Ia supernovae (other than involving a white dwarf driven over the Chandrasekhar mass limit via accretion of some sort) several scenarios predict timescales after formation of the progenitor main sequence stars, for significant chemical enrichment by Type Ia supernovae, of around 1 Gyr (e.g. Smecker & Wyse 1991; Yungelson & Livio 1998). One does not require that the entire stellar halo formed on this timescale, only that self-enriching regions formed stars this rapidly, and there was little cross-contamination between non-synchronized regions. Indeed, an attractive mechanism to produce only a short duration to star formation is a Type II supernovae-driven wind, more naturally-produced if the star-forming regions have local potential wells significantly shallower than does the halo as a whole.

Thus one is led to a picture wherein the field stars of the halo form in fragile fragments/blobs, within which feedback from massive stars can be sufficiently disruptive that star formation is truncated, and a large part of the remaining interstellar medium ejected. The feedback and mass loss could be sufficient to unbind the ‘fragment’ totally, or it could be that the new virial equilibrium of the ‘fragment’ is sufficiently fragile that external processes such as tidal forces can disrupt the ‘fragment’. The ejected gas will cool and dissipate, and with angular momentum conservation will settle into the central regions of the overall larger-scale potential well of the proto-Galaxy, somewhat as envisaged by Eggen, Lynden-Bell & Sandage (1962). This could form the central bulge. As pointed out by Hartwick (1976), one can understand the low mean metallicity of the halo within models with a fixed stellar IMF if there is gas removal during the formation of the halo stars – a reduction of a factor of around 10 in the mean metallicity, compared to theoretical expectations with no gas loss, is required for the stellar halo, and this is achieved by removing around this ratio of mass during star formation. Thus one would predict a central bulge some 10 times more massive than the stellar halo, in agreement with estimates of the masses of stellar halo and bulge (Carney *et al.* 1990; Wyse & Gilmore 1992).

There is little scatter in the trend of element ratios, such as $[\text{Mg}/\text{Fe}]$ against $[\text{Fe}/\text{H}]$, for the bulk of the stellar halo (e.g. Nissen *et al.* 1994), consistent with enrichment by stars with a fixed massive-star IMF, and furthermore, one close to that observed in star-forming regions locally today (see Wyse 1998 for a review). The lack of scatter also implies rather efficient mixing, and one might expect to see some scatter at the lowest levels of enrichment, when very few supernovae have contributed (cf. Audouze & Silk 1995; Tsujimoto, Shigeyama & Yoshii 1999), and this is indeed observed (McWilliam *et al.* 1995; Ryan, Norris & Beers, 1996; Ryan this volume).

In this picture of star-forming fragments in the halo, there is the possibility that a few fragments had a deep enough potential-well to sustain star formation and self-enrich with the products of Type Ia supernovae. Further, with asynchronous onsets of star formation in different regions, there could be enrichment of a given ‘fragment’ by a Type Ia supernova whose progenitors were formed in a different fragment. Thus one might expect to see at least some stars in the halo now with values of the element ratios reflecting ‘extra’ iron from Type Ia supernovae (note that the fact that this is not generally observed for halo stars is further motivation for the prompt removal of gas from the halo to the bulge; Wyse & Gilmore 1992). Indeed, a subset of halo stars, apparently biased towards the metal-rich halo, i.e. $[\text{Fe}/\text{H}] > -1$ dex (Nissen & Schuster 1997) and/or extremely high-energy orbits (Carney *et al.* 1997; King 1997; Ivans *et al.* this volume) have now been observed to have low values of $[\text{Mg}/\text{Fe}]$, close to or below the solar value, consistent with pre-enrichment by a combination of Type I and Type II supernovae.

Fig. 5 is taken from Gilmore & Wyse (1998) and based on the data of Nissen & Schuster (1997) for their survey of disk and halo stars of similar metallicities, where ‘disk’ and ‘halo’ are defined kinematically in terms of orbital rotational velocity. This is one of the few datasets where both disk and halo stars have been analysed together, allowing a direct comparison of their elemental abundances. As can be seen, there are both disk and halo stars with enhanced magnesium, $[\text{Mg}/\text{Fe}] \sim +0.3$, consistent with being enriched by massive stars with the same, invariant IMF. The halo stars and disk stars with low values of $[\text{Mg}/\text{Fe}]$ are as expected for some enrichment from Type Ia supernovae. Note that in Fig. 5 the halo stars lie along the locus for a lower star-formation rate than do the disk stars, but this may be a manifestation of the fact that gas outflows, as invoked above to have operated in halo star-forming regions, reduce the efficiency of star formation and mimic a lower value.

The lower values of the α -elements in these low-metallicity stars (remember that the higher metallicity part of the halo is still well below solar metallicity) are as predicted for the metal-

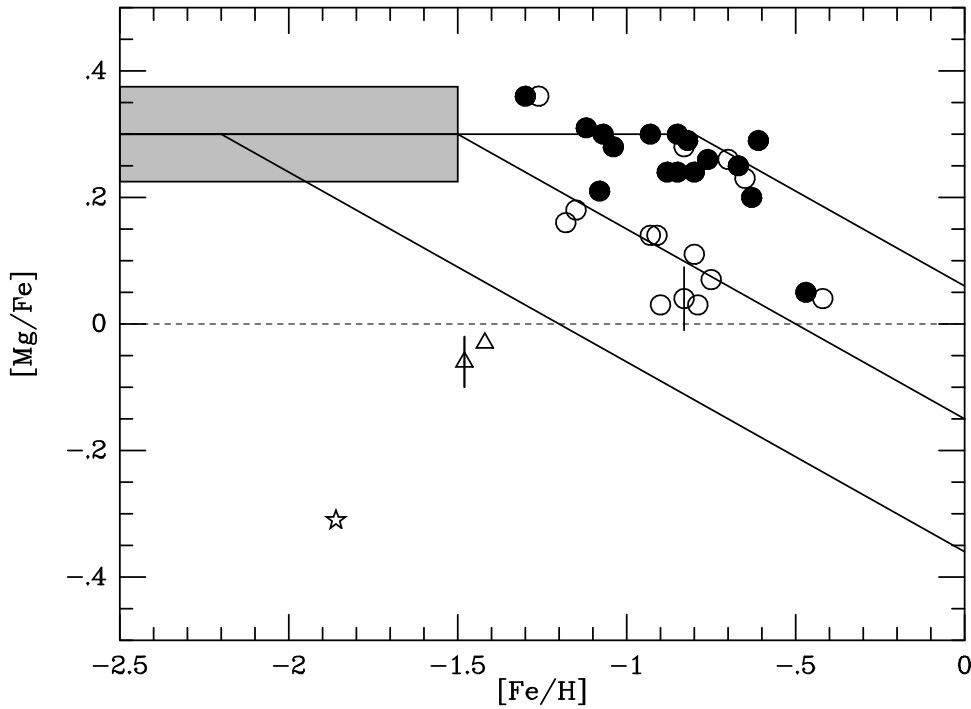


Figure 5: Element ratio $[Mg/Fe]$ against iron abundance for the kinematically-defined disk stars (open circles) and the kinematically-defined halo stars (filled circles) from Nissen & Schuster (1997), together with the metal-poor anomalous halo stars from King (1997; triangles) and from Carney *et al.* (1997; star symbol); uncertainties in $[Mg/Fe]$ as indicated. The lines drawn to guide the eye are schematic trends of $[Mg/Fe]$ against $[Fe/H]$ for closed, self-enriching systems of invariant IMF and a range of star formation rates; a higher star formation rate leads to a higher value of the iron abundance at the onset of Type Ia supernovae, which produces a downturn in this plot. The shaded region indicates the locus of normal halo stars. There are three main points to this figure (based on figure 1 of Gilmore & Wyse 1998), the first being that the value of the Type II $[Mg/Fe]$ ‘plateau’ is the same for both the halo and disk stars, the second being that the vast majority of ‘metal-rich’ halo stars have lower values of $[Mg/Fe]$ than this canonical ‘plateau’ value, consistent with having ‘extra’ iron from Type Ia supernovae, and the third being that the typical elemental abundances of disk and halo stars of the same iron abundance are different, supporting a disk/halo discontinuity.

poor stars in dwarf companion galaxies to the Milky Way (Gilmore & Wyse 1991). This, combined with the fact that the serendipitously-identified metal-poor halo stars with anomalously low values of the ratio of magnesium-to-iron are on retrograde orbits, led to the speculation that these stars may have been captured (accreted) from external satellite galaxies (Carney *et al.* 1997; King 1997). However, there is no tendency for the low $[Mg/Fe]$ stars in the Nissen & Schuster sample to be on retrograde orbits. All the ‘low-alpha-elements’ stars are, however, on very high-energy radial orbits, with apoGalacticon greater than 15 kpc, and periGalacticon less than 1 kpc. These are very unlikely orbits for stars accreted from satellite galaxies, a term that implies a separate identity for a significant time. In models which invoke fragmentation within a gaseous proto-halo, fragments which probe the denser inner Galaxy are naturally themselves more dense (e.g. Fall & Rees 1985), and likely to have deeper local potential wells, and be able to self-enrich longer. Thus a trend that the halo stars with evidence for enrichment by Type Ia

supernova be on orbits of low periGalacticon (but not necessarily high apoGalacticon) may be understood, without any need to appeal to ‘accretion’. Further, Stephens (1999) has analysed a sample of halo stars selected to be on extreme orbits, and interprets the elemental abundance patterns as being no different from those of the rest of the halo. However, there is clearly a need for a large, uniformly-analysed sample over the entire range of kinematics and metallicity of the stellar halo.

A further point evident from Fig. 5 is that the typical elemental abundances of disk and halo stars of the same iron abundance are different, supporting a disk/halo discontinuity in chemical enrichment, and consistent with the different specific angular momentum content of disk and halo (Wyse & Gilmore 1992) – the local halo did *not* pre-enrich the local disk. These metal-rich halo stars are a small fraction of the locally-defined stellar halo. However, it must be noted that the *global* metallicity distribution of the stellar halo is poorly defined (in particular for the inner halo), as are the wings of the metallicity distribution function for more locally-defined samples. The overlap between stellar halo and (thick) disk at metallicities around $[\text{Fe}/\text{H}] = -1$ is a particular focus of our ongoing 2dF project (Gilmore, Wyse, Norris & Freeman).

3.2 Kinematics & Age

Moving groups of stars in the halo have been searched for by many groups, with limited success in that the signatures are usually of low statistical weight (e.g. Arnold & Gilmore 1992; Majewski, Munn & Hawley 1996; Helmi & White 1999; Helmi, White, de Zeeuw & Zhao 1999). A complication in the interpretation of moving groups is that all substructure in the Galaxy is subjected to tidal effects. For example, the present system of globular clusters may well be a mere shadow of the initial retinue (e.g. Gnedin & Ostriker 1997) and one expects e.g. tidal arms and streamers from the surviving globular clusters (see Grillmair, Freeman, Irwin & Quinn, 1995; Meylan, this volume).

The unique substructure that has been found by virtue of its location in position–radial velocity phase space is the Sagittarius Dwarf Spheroidal galaxy (Ibata, Gilmore & Irwin 1994, 1995). This satellite companion to the Milky Way was noticed by its discoverers, in the course of their survey of stars in the bulge of the Milky Way, as a distinct set of stars with ‘anomalous’ kinematics to be actually members of the bulge. The stars with these very well-defined, but anomalous, kinematics were localised in a subset of their lines-of-sight, and could be identified with a feature (the red clump of helium-burning stars) in the colour-magnitude diagram for all stars in those fields. The center of the Sagittarius dwarf is located some 24 kpc from the Sun, on the other side of the Galactic centre. The preliminary proper motion and orbit derived by Ibata *et al.* (1997) for this dwarf galaxy imply that it has a radial period of less than 1 Gyr, and a periGalacticon of only ~ 12 kpc. Without a significant amount of dark matter to bind it, the Sagittarius dSph would be unable to survive more than a couple of such close periGalactic passages (e.g. Velazquez & White 1995), but its dominant stellar population has an age of ~ 10 Gyr. Either the orbital parameters have been recently changed (e.g. Zhao 1998), or the dwarf is more robust than it looks (Ibata *et al.* 1997).

The more diffuse outer regions of the Sagittarius dSph are more susceptible to tidal stripping, and intriguing observations of stars with kinematics such that they plausibly could have been removed from the dwarf galaxy on a previous periGalactic passage have been reported by Majewski *et al.* (1999), and analysed in Johnston *et al.* (1999). Further, this interpretation is consistent with the photometric detection of member stars some 30° from the centre of the Sagittarius dwarf by Mateo, Olszewski & Morrison (1998).

A few of the globular clusters of the Milky Way have clearly younger ages than the vast

majority of globular clusters and have been suggested as candidates for being accreted from companion galaxies (e.g. Fusi Pecci *et al.* 1995). Indeed it is now recognised that this group includes actual members of the Sagittarius dwarf's retinue of clusters (e.g. Ibata *et al.* 1995; Da Costa & Armandroff 1995), and should not be included in the census of Milky Way clusters. The globular cluster M54 is situated at the centre of the Sagittarius dwarf, no doubt partly motivating the interpretation of the globular cluster ω Cen as the nucleus of an accreted dwarf galaxy (Majewski *et al.* this volume; Wallerstein & Hughes, this volume). The very different stellar populations in a typical companion galaxy and in the stellar halo provide strong constraints on general accretion and disruption of satellite galaxies as a means to form the stellar halo (Unavane, Wyse & Gilmore 1996; Gilmore this volume). Indeed significant (greater than $\sim 10\%$ of the stellar halo) accretion cannot have occurred from typical dwarf galaxies, with their large range of stellar ages, subsequent to the formation of these intermediate-age stars, and is thus restricted to ≥ 8 Gyr ago.

Several analyses of chemistry and kinematics for samples of halo stars have found evidence for differences between the 'far' halo and the 'inner' halo e.g. Majewski (1992), Norris (1994), Carney *et al.* (1996), Layden (1998), Carney (this volume). This would plausibly reflect differences in the dominant physical mechanisms at formation. However, for any reasonable halo profile the fractional mass of the 'far' halo is small (see e.g. Fig. 1 of Unavane, Wyse & Gilmore 1996). Further, Carney (private communication) has found intriguing differences in binary fraction between the 'far' halo and the 'inner' halo, in that the 'far' halo has a significantly lower fraction. Mass transfer in close binary systems could certainly affect surface elemental abundances, and the 'kick' from disruption could perhaps produce extreme kinematics. Clearly more work is warranted.

3.3 Faint Stellar Luminosity Function and IMF

As discussed briefly above in Sect. 32.1, the elemental abundances for the bulk of the stellar halo and the disk suggest that the massive star IMF was, and is, invariant. Low-mass stars, those with main-sequence lifetimes that are of order the age of the Universe, provide more direct constraints on the IMF when they formed. Star counts in systems with simple star-formation histories are particularly straightforward to interpret, and those in 'old' systems allow one to determine the low-mass stellar IMF at large look-back times and thus at high redshift. The dwarf spheroidal satellite galaxies of the Milky Way are now accessible for this experiment using the Hubble Space Telescope. These galaxies are particularly interesting since their internal kinematics suggest that they are among the most dark-matter-dominated systems known (reviewed by Mateo 1998), and this dark matter must be cold to form structures on such small scales (e.g. Tremaine & Gunn 1978; Gerhard & Spergel 1992), but at least the gas-rich dwarfs for which rotation curves can be measured do not fit the predictions of non-baryonic CDM (e.g. Moore 1984). Could the dark matter be cold since it is baryonic and radiated away binding energy? Might the dark matter then be associated with faint stars?

The Ursa Minor dwarf spheroidal galaxy (dSph) is suitable for study, being relatively nearby (distance ~ 70 kpc), and, unusually for a dwarf spheroidal galaxy, having a stellar population with narrow distributions of age and of metallicity (e.g. Hernandez, Gilmore & Valls-Gabaud 1999), remarkably similar to that of a classical halo globular cluster such as M92 or M15, i.e. old and metal-poor ($[\text{Fe}/\text{H}] \sim -2.2$ dex). The integrated luminosity of the Ursa Minor dSph ($L_V \sim 3 \times 10^5 L_\odot$) is also similar to that of a globular cluster. However, the central surface brightness of the Ursa Minor dSph is only 25.5 V-mag/sq arcsec, corresponding to a central luminosity density of $0.006 L_\odot \text{pc}^{-3}$, many orders of magnitude lower than that of a

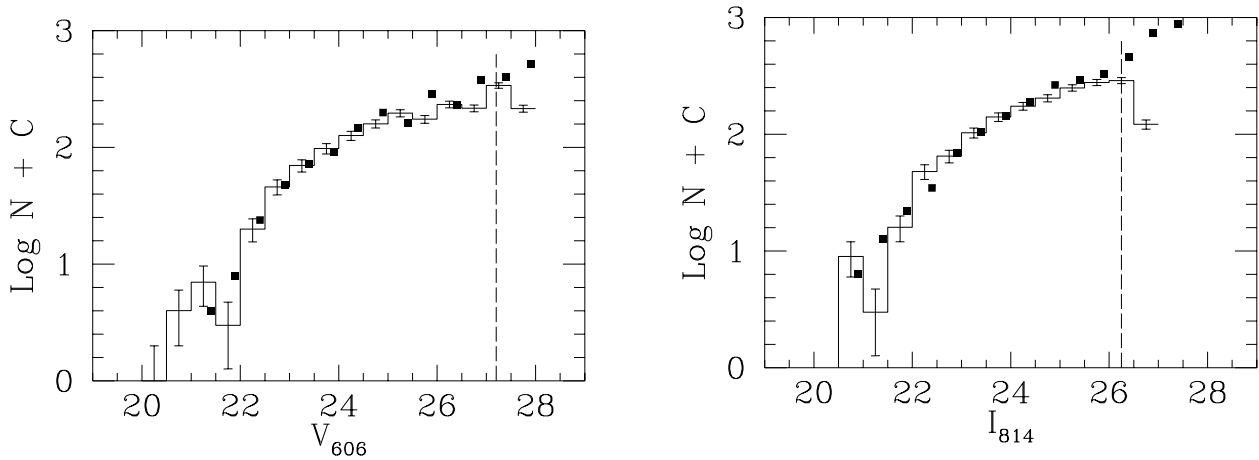


Figure 6: Comparison between the completeness-corrected Ursa Minor luminosity functions (histograms; 50% completeness indicated by the vertical dashed line) in the V-band (left panel) and the I-band (right panel) and the same for M92 (points, moved to same distance as the Ursa Minor dSph; from Piotto *et al.* 1997). The luminosity functions for the globular cluster and the dwarf spheroidal galaxy are indistinguishable.

typical globular cluster. Further, again in contrast to globular clusters, its internal dynamics are dominated by dark matter, with $(M/L)_V \sim 80$, based on the relatively high value of its internal stellar velocity dispersion (Hargreaves *et al.* 1994; see review of Mateo 1998).

We obtained deep imaging data with the Hubble Space Telescope, using WFPC2 (V-606 & I-814), STIS (LP optical filter) and NICMOS (H-band), in a field close to the center of the Ursa Minor dSph (program GO 7419: PI Wyse, Co-Is Gilmore, Tanvir, Gallagher, Smecker-Hane, Feltzing & Houdashelt). As shown in Fig. 6 (from Feltzing, Gilmore & Wyse 1999), the faint optical stellar luminosity function of the Ursa Minor dSph is also remarkably similar to that of M92, down to our limiting apparent magnitude with WFPC2 data, which corresponds to around four-tenths of a solar mass. The M92 data (Piotto, Cool & King 1997) should be a reliable estimate of the global initial luminosity (and mass) function in this cluster, being obtained at intermediate radius within the globular cluster, minimising internal dynamical effects, and the cluster itself is on an orbit that minimises external tidal effects. The similarity of age and metallicity between these two systems means that the comparison of the main sequence faint luminosity functions is effectively a comparison of stellar initial mass functions. And as can be seen in the figure, these two luminosity functions are remarkably similar, down to our completeness limit corresponding to around $0.4 M_\odot$. Thus two systems that differ in mass to light ratio by a factor of roughly 50, and in stellar surface density by orders of magnitude, formed stars with the same initial mass function. A consistent result, but for a significantly less-deep luminosity function reaching to $0.6 M_\odot$, was obtained for the Draco dSph by Grillmair *et al.* (1998).

The apparent insensitivity of the stellar IMF to any parameter that physical intuition tells one should be important is remarkable (see papers in Gilmore & Howell, 1998). However, it allows a reliable simplifying assumption – an invariant IMF – to be made when modelling the evolution of galaxies.

The identity of the dark matter in dSph galaxies remains a puzzle; we are obtaining deeper data and should be able to push the stellar luminosity function somewhat fainter. However, low-mass stars do not look likely candidates.

4 Summary and Conclusions

‘Scenario’ rather than ‘model’ is appropriate for the title of this paper, since we do not yet have a clear understanding of the mechanisms by which disk galaxies form and evolve. However, it is clear that substructure plays an important role in galaxy formation and evolution. For example, the thick disk is plausibly a remnant of the last significant merger event in the history of the Milky Way; the remnant satellite may have been detected. That this last significant merger was a long time ago is apparently in conflict with flat CDM-dominated models. Further, while accretion of stars from fragile satellite galaxies may make a significant contribution to the outer halo, this is not the case for the bulk of the halo; late accretion in particular is ruled out by the uniform old age of the bulk of the halo stars. A simplifying factor for models of galaxy evolution is that the stellar IMF is apparently invariant.

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